Validation of HelioClim-3 version 4, HelioClim-3 version 5 and MACC-RAD using 14 BSRN stations

Claire Thomas, Etienne Wey, Philippe Blanc, Lucien Wald, Mireille Lefèvre

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 91 (2016) 1059 – 1069

Energy Procedia

SHC 2015, International Conference on Solar Heating and Cooling for Buildings and Industry

Validation of HelioClim-3 version 4, HelioClim-3 version 5 and MACC-RAD using 14 BSRN stations

Claire Thomas[a], Etienne Wey[a], Philippe Blanc[b], Lucien Wald[b], Mireille Lefèvre[b]

[a]TRANSVALOR, Parc de Haute Technology, 694 Av. du Doc. Maurice Donat, 06255 Mougins
[b]MINES ParisTech, PSL-Research University, CS10207, 06904 Sophia Antipolis Cedex

Abstract

This communication presents the results of a comparison of three satellite-derived databases covering Africa, Europe, Middle East and part of South America, against corresponding 15 min irradiations of very high quality measured by fourteen Baseline Surface Radiation Network (BSRN) stations. The three databases are accessible via the SoDa Service website, and are the two latest versions of HelioClim-3: versions 4 (HC3v4) and 5 (HC3v5), and the MACC-RAD database. The comparison was performed for durations of 15 min, 1 h, 1 day and 1 month for both the global irradiation received on a horizontal surface (GHI) and the direct irradiation received on a plane normal to sun rays (DNI).

It is found that the three satellite-derived radiation databases exhibit satisfactory performances. For most of the fourteen locations, HC3v5 surpasses HC3v4 and MACC-RAD, with a bias ranging from -4 to 5% for the GHI and for all tested duration. The correlation coefficient is large for all databases and most often greater than 0.92 for 15 min and 0.98 for daily irradiation for GHI. The RMSE is fairly constant for all locations for 15 min and is approximately 20 kWh m^{-2} –slightly greater for MACC-RAD.- For daily irradiation, it ranges between 300 and 400 kWh m^{-2} for HC3v5, 300 and 500 kWh m^{-2} for HC3v4, and 400 and 550 kWh m^{-2} for MACC-RAD. Bias for the DNI is larger in absolute values than for GHI for all databases: -12 to 10% for HC3v5. The correlation coefficient is most often greater than 0.68 for 15 min and 0.84 for daily irradiation. The RMSE for 15 min ranges between 46 and 60 kWh m^{-2} for HC3v5, 46 and 63 kWh m^{-2} for HC3v4, and 48 and 66 kWh m^{-2} for MACC-RAD. For daily irradiation, it ranges between 1100 and 1600 kWh m^{-2} for HC3v5, between 1300 and 1700 kWh m^{-2} for HC3v4, and between 1000 and 1850 kWh m^{-2} for MACC-RAD. The MACC-RAD resource show promises provided the model for cloud properties is improved.

Peer-review by the scientific conference committee of SHC 2015 under responsibility of PSE AG

Keywords: irradiation; satellite; HelioClim-3; MACC-RAD; validation; BSRN ground stations; Meteosat Second Generation; SoDa Service

Peer-review by the scientific conference committee of SHC 2015 under responsibility of PSE AG
doi:10.1016/j.egypro.2016.06.275

1. Introduction

Knowledge of the solar resource at ground level is a critical issue for developing solar energy. Of particular interest are archives, recent and real time data, and more lately forecast estimates of the surface solar irradiation (SSI), i.e. the downwelling broadband solar irradiation received at ground level. Many studies have demonstrated the potential of satellite images to assess the SSI [1], and their use within the framework of feasibility studies of solar plants.

The SoDa Service (www.soda-pro.com) is dedicated to professionals in solar energy [2] and provides an access to different solar-related resources, in particular to the HelioClim-3 (abbreviated HC3) and the MACC-RAD databases. They contain SSI data over the area observed by the Meteosat Second Generation (MSG) satellite, i.e. Europe, Africa, the eastern part of South America and Middle East. HC3 is available for free on 2004-2005, and for pay on more recent dates via annual subscriptions or on-delivery value-added services. It is widely used by professionals in solar energy, with more than 50 current annual subscriptions. The MACC-RAD database [3] is an outcome of the successive European-funded MACC (Monitoring Atmospheric Composition & Climate) projects and is available for free via the MACC portal and SoDa.

This communication presents the results of an objective evaluation of HC3 version 4 (HC3v4), HC3 version 5 (HC3v5) and MACC-RAD against high quality measurements of fourteen Baseline Surface Radiation Network (BSRN) stations.

2. The HelioClim-3 (HC3) and MACC-RAD databases

2.1. HC3

MSG images are routinely processed with the Heliosat-2 method [1] every 15 min to update the HC3 database [4]. Heliosat-2 combines a clear sky model with a “cloud index”. The cloud index approach is based on the assumption that the appearance of a cloud over a pixel results in an increase of reflectance in visible imagery; the attenuation of the downwelling shortwave irradiance by the atmosphere over a pixel is related to the magnitude of change between the reflectance that should be observed under a cloud-free sky and that currently observed. This magnitude of change is quantified by the cloud index.

HC3v4 and HC3v5 are the two most advanced versions of HC3. HC3v4 uses the ESRA clear-sky model [5] with the climatological database of the Linke turbidity factor of Remund *et al.* [6] as input. The major drawback of this database is that it is never updated to take into account the attenuation or increase of the atmosphere turbidity due to local effects such as maritime inputs, volcanoes, fires, evolution of the water vapor content, pollution… The McClear clear sky model [7] is also an outcome of the MACC projects and provides updated information on the content of the cloud-free atmosphere for the whole world every 3 h since 2003. HC3v5 is an attempt to overcome the limitation of this climatological database by combining HC3v4 and the McClear model [8].

HC3 estimates of SSI are available at integration periods (or time steps or summarizations) of 15 min, 1 h, 1 day and 1 month. The temporal coverage of data is from 2004-02-01 up to current day-2 for the version 5, and day-1, real time and even d+1 forecast data for version 4. HC3 provides global 15 min irradiation received on horizontal surface (GHI for global horizontal irradiation), on which decomposition models are applied to compute all the components of the radiation over a horizontal, fix-tilted and normal plane for the actual weather conditions. When a request is launched, post-processing layers are applied for instance to modulate the radiation values inside the MSG pixels to take into account the actual elevation of the required location, or to compute the shadowing effect of the far horizon. HC3 time series can be manually retrieved either via the SoDa website, or automatically via a machine-to-machine access. Several other value-added services based on this resource are also available as a one-shot request, such as the purchase of a volume of HC3 time series or Typical Meteorological Years on a given area, irradiation maps, in-situ measurement completion…

2.2. MACC-RAD

MACC-RAD time series of irradiation values can also be retrieved from the SoDa portal. MACC-RAD is computed using the Heliosat-4 method which models radiative transfer to compute the SSI. The SSI can be approximated as the product of the irradiance under clear atmosphere from McClear by a modification factor due to APOLLO cloud properties and ground albedo derived from MODIS imagery [9]. The database of APOLLO cloud properties is the property of the German center of research DLR, and results from the processing of different channels of the MSG satellite.

The MACC-RAD service provides time series of global, direct, and diffuse irradiations on horizontal surface, and direct irradiation on plane normal to sun rays (DNI for direct normal irradiation) for the actual weather conditions. The time coverage of data is from 2004-02-01 up to 2 days ago. Data are available with a time step ranging from 15 min to 1 month. MACC-RAD can be accessed directly on the SoDa website using the corresponding interface, or using the interoperable OGC-compliant Web Processing Service [7].

MACC-RAD and McClear services are currently pre-operational and will become operational in Jan. 2016. As the generation of a MACC-RAD time series consumes a lot of CPU time and memory, the number of requests is so far limited to 5 per day per user, but a lot of effort is done to increase the speed of access to this service.

3. Validation against the measurements from fourteen BSRN stations

3.1. Brief overview of the fourteen BSRN stations

The Baseline Surface Radiation Network (BSRN) is a collection of measurements of GHI, diffuse irradiations on horizontal surface, and DNI of high quality suitable for validation [10][11][12]. Measurements are acquired every 1 min. Figure 1 and table 1 give the locations and the main characteristics of the fourteen BSRN stations used for the quality assessment of the data, located in the MSG coverage.

Fig. 1. Locations of the fourteen BSRN stations used for the quality assessment of HC3v4, HC3v5 and MACC-RAD

Table 1. List of the fourteen BSRN stations, in decreasing latitudes.

Station	Code	Country	Latitude (°)	Longitude (°)	Altitude (m)	Period of data availability
Lerwick	LER	UK	60.133	-1.183	84	2004-02-01 to 2007-12-31
Toravere	TOR	Estonia	58.254	26.462	70	2004-02-01 to 2014-12-31
Lindenberg	LIN	Germany	52.210	14.122	125	2004-02-01 to 2007-12-31
Cabauw	CAB	Netherlands	51.971	4.927	0	2005-01-01 to 2014-12-31
Camborne	CAM	UK	50.217	-5.317	88	2004-02-01 to 2007-12-31
Palaiseau	PAL	France	48.713	2.208	156	2004-02-01 to 2013-12-31
Payerne	PAY	Switzerland	46.815	6.944	491	2004-02-01 to 2011-12-31
Carpentras	CAR	France	44.083	5.059	100	2004-02-01 to 2014-12-31
Cener	CEN	Spain	42.816	-1.601	471	2009-01-01 to 2013-12-31
Sede Boqer	SBO	Israel	30.905	34.782	500	2004-02-01 to 2012-12-31
Tamanrasset	TAM	Algeria	22.780	5.510	1385	2004-02-01 to 2014-12-31
Brasilia	BRB	Brazil	-15.601	-47.713	1023	2006-01-01 to 2013-12-31
Sao Martinho da Serra	SMS	Brazil	-29.443	-53.823	489	2006-01-01 to 2012-12-31
De Aar	DAA	South Africa	-30.667	23.993	1287	2004-02-01 to 2005-12-31

3.2. Protocol of evaluation and quality check of the BSRN measurements

This section describes the protocol for the evaluation of an estimated dataset against a reference. In our case, the protocol concerns the comparison of satellite-based irradiation values against the high quality measurements of the fourteen BSRN stations listed in the previous table.

Prior the comparison at different summarizations, a thorough quality check procedure as recommended by [12] and [13] has been applied onto the 1 min BSRN data. The major steps can be summarized as follows:

- Set night, sunrise and sunset values to zero,
- Set to "Not a Number" (NaN) the values of the estimates when the references are missing, and reverse,
- Discard values beyond "extremely rare limits" and "physical possible limits",
- Perform the consistency checks when the three radiation components are available.

Then, a temporal aggregation is performed to generate the values at the different summarizations. This procedure is of utmost importance since it directly impacts the validation results. Our approach is as follows:

- Generate the 15 min irradiation from the 1 min BSRN measurements if at least 85% of the slots are available. Then apply an "intelligent interpolation" taking into account the sun position at each minute to synthesize the 15 min data to fill gaps. Compute the quantities summarizing the deviation at 15 min.
- Generate the hourly, daily and monthly irradiation by summing up the 15 min irradiation if at least respectively 75%, 65% and 50% of the slots are available. No temporal interpolation is applied, leading to partial sums. Compute the quantities summarizing the deviation at the hourly, daily and monthly time steps.

Table 2 gives an overview of the quantities that have been computed at the different time steps to assess the quality of the three different satellite-based databases.

Table 2. Names and formula of the quantities summarizing the deviation at a given duration.

Name of the index	Formula
Observation at instant k	x_k
Estimation (model) at k	y_k
Number of samples (Number of coincident values (x_k, y_k))	N
Mean observed value	$m_x = \frac{1}{N}\sum_{k=1}^{N} x_k$
Standard deviation of the observation	$\sigma_x = \sqrt{\frac{1}{N}\sum_{k=1}^{N}(x_k - m_x)^2}$
Deviation at k	$\delta_k = (y_k - x_k)$

Bias (mean deviation)	$b = \frac{1}{N}\sum_{k=1}^{N}\delta_k$
Relative bias	$rb = \frac{b}{m_x}$
Root Mean Square Error	$RMSE = \sqrt{\frac{1}{N}\sum_{k=1}^{N}\delta_k^2}$
Relative RMSE	$rRMSE = \frac{RMSE}{m_x}$
Standard deviation of δk	$\sigma = \sqrt{\frac{1}{N}\sum_{k=1}^{N}(\delta_k - b)^2}$
Relative standard deviation	$r\sigma = \frac{\sigma}{m_x}$
Relationship between b, *RMSE* and σ	$RMSE^2 = b^2 + \sigma^2$
Covariance of x and y	$\sigma_{xy} = \frac{1}{N}\sum_{k=1}^{N}(x_k - m_x)(y_k - m_y)$
Correlation coefficient	$CC = \frac{\sigma_{xy}}{\sigma_x \sigma_y}$

3.3. Presentation of the validation results for the Carpentras station

The validation results for the HC3 version 4, version 5 and MACC-RAD databases and for the daily and 15 min summarizations (Tables 3 to 10) have been placed in Appendix. They are also available on the SoDa website, along with results for the hourly and monthly summarizations at the following urls: http://www.soda-pro.com/help/helioclim/helioclim-3-validation/bsrn-stations and http://www.soda-pro.com/help/macc-rad/validation for respectively HelioClim-3 and MACC-RAD validations results. From the various quantities summarized in Table 2 and computed in this validation process, the following figures are presented:

- The bias, and relative bias in percent,
- The root mean square error (RMSE), and relative RMSE in percent,
- And the correlation coefficient.

In conjunction with these statistical results, the quality assessment routines generate a series of 2-D histograms to enable a visual inspection of the results. In the “y” axis is the estimation (or satellite measurements), and the “x” axis is the reference, represented here by the BSRN station measurements. Figures 2 (a) to (f) present the 2-D histograms of 15 min satellite-based GHI and DNI irradiation values versus the corresponding measurements for the station of Carpentras. On the upper left corner of each graph, the main figures are reminded. In this particular case, HC3 reaches a better performance, and in particular version 5, in terms of relative bias with values ranging from -1.7% to 1.6% for both radiation components, against -5.1% to 5.6% for MACC-RAD. This remark is in agreement with the results obtained on most of the other BSRN stations.

The relative RMSE exhibits satisfactory results for the GHI components, with values ranging from 16.2% for the HC3v5 values to 19.6% for MACC-RAD. This is in line with the graphical representation of the data where most of the points are located along the y=x axis, meaning that the estimation is correctly reproducing the reference data. The correlation coefficient confirms that HC3v5 returns the best results for the GHI component.

For the DNI component, the relative RMSE is ranging from 28.7% for MACC-RAD to 32.7% for HC3v4. RMSE gives an idea of the “spreading” of the data around the bias. For the station of Carpentras, we can conclude that despite a higher bias, MACC-RAD slightly outperforms the two versions of HC3 for the DNI component in terms of relative RMSE and correlation coefficient.

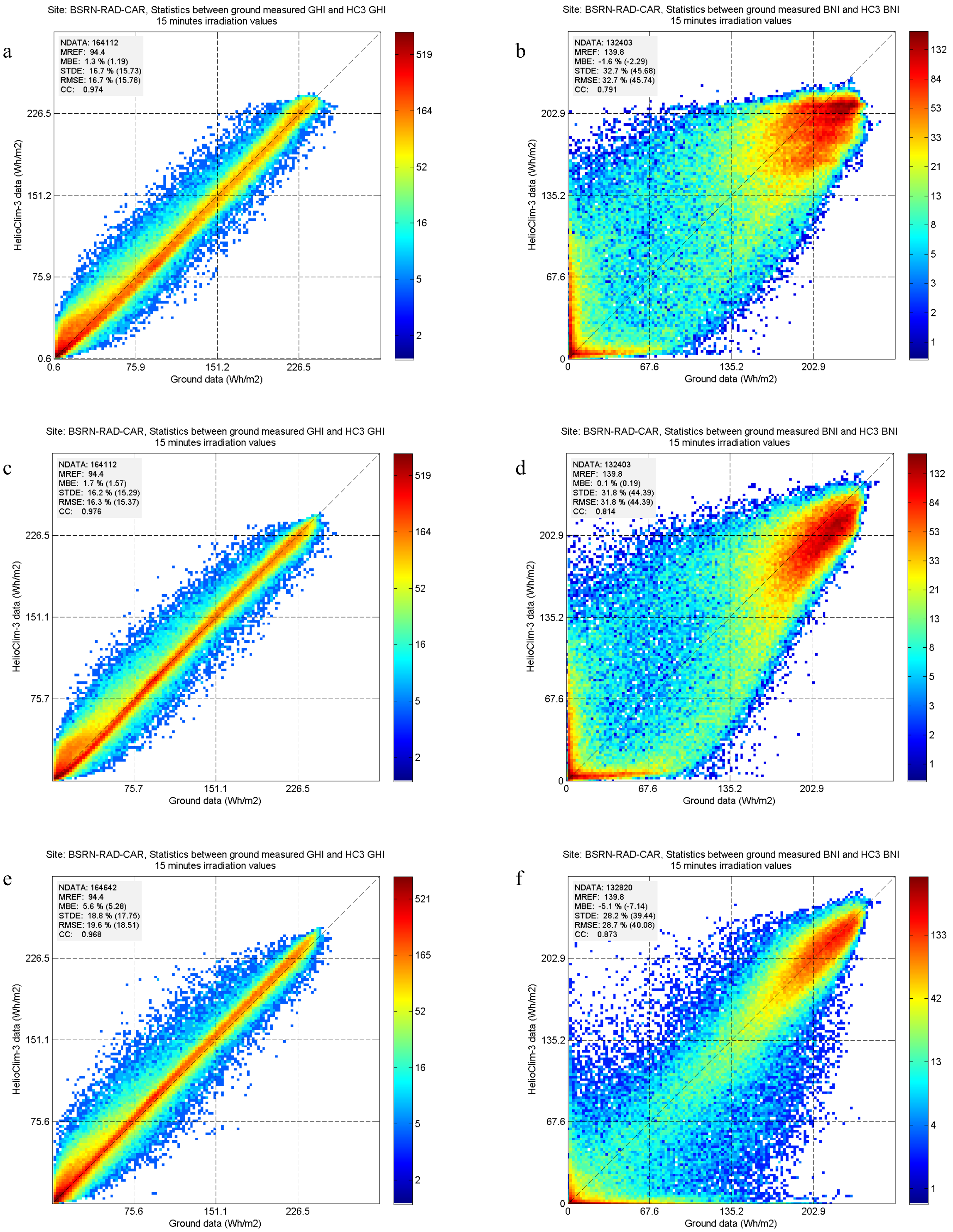

Fig. 2. (a) 2-D histogram of the 15 min HC3v4 GHI values versus the measurements of the BSRN station of Carpentras; (b) HC3v4 DNI; (c) HC3v5 GHI; (d) HC3v5 DNI; (e) MACC-RAD GHI; (f) MACC-RAD DNI

3.4. Validation results: global conclusions

If we set apart the northern stations (Toravere and Lerwick) where the three satellite-based databases face difficulties in reproducing the measurements, here are the global conclusions for the fourteen BSRN stations: In most of the tested locations, HC3v5 surpasses HC3v4 and MACC-RAD, and exhibits a bias ranging from -4 to 5% for the GHI and for all tested durations. The correlation coefficient is large for all databases and most often greater than 0.92 for 15 min and 0.98 for daily irradiation. The RMSE for all databases is fairly constant for all locations for 15 min and is approximately 20 kWh m^{-2} –slightly greater for MACC-RAD. For daily irradiation, it ranges between 300 and 400 kWh m^{-2} for HC3v5, 300 and 500 kWh m^{-2} for HC3v4, and 400 and 550 kWh m^{-2} for MACC-RAD.

Bias for the DNI is larger in absolute values than for GHI for all databases: -12 to 14% for HC3v5, and the range is slightly wider for v4 and MACC-RAD. The correlation coefficient is often greater than 0.68 for 15 min and 0.84 for daily irradiation. The RMSE for 15 min ranges between 46 and 60 kWh m^{-2} for HC3v5, 46 and 63 kWh m^{-2} for HC3v4, and 48 and 66 kWh m^{-2} for MACC-RAD. For daily irradiation, it ranges between 1100 and 1600 kWh m^{-2} for HC3v5, between 1300 and 1700 kWh m^{-2} for HC3v4, and between 1000 and 1850 kWh m^{-2} for MACC-RAD.

This global investigation of the statistical results leads to the final conclusion that HC3v5 outperforms the two other databases, for all tested summarizations and all radiation components. This result is coherent for the version 4 since the use of McClear in the version 5 was expected to improve the results obtained for this prior version. MACC-RAD exhibits very promising results, in particular for the DNI component. So far, the major failure of this database is that a few errors have been reported in the cloud detection for some particular weather conditions. However, we are convinced that the new generation of APOLLO cloud properties will at least partly solve this issue, and that MACC-RAD will reach soon a quality similar or even better than version 5 during its operational phase.

4. Conclusion

The validation campaign conducted between HC3v4, HC3v5, and MACC-RAD versus the measurements from fourteen BSRN stations exhibit satisfactory performances. In most cases, HC3v5 surpasses HC3v4 and MACC-RAD. McClear is still in its pre-operational phase, nevertheless the results demonstrate it is now a robust and already reliable database, while the cloud property model exploited in MACC-RAD still needs a few adjustments.

Acknowledgements

The authors thank all ground station operators of the BSRN network for their valuable measurements and the Alfred-Wegener Institute for hosting the BSRN website. The research leading to these results has been partly undertaken within the Task #46 of the Solar Heating and Cooling Implementing Agreement of the International Energy Agency. It has received funding from the French Agency ADEME, research grant no. 1105C0028, and from the European Union’s Seventh Framework Programme (FP7/2007-2013) under Grant Agreement no. 218793 (MACC project) and no. 283576 (MACC-II project) and from the European Union’s Horizon 2020 Programme (H2020/2014-2020) under grant agreement no. 633081 (MACC-III project). The MACC (Monitoring Atmospheric Composition and Climate) projects are preparatory projects for Europe’s Copernicus Atmosphere Monitoring Service (CAMS).

Appendix A. Validation results

The results of the validation for the monthly and the hourly summarizations are available at: http://www.soda-pro.com/help/helioclim/helioclim-3-validation/bsrn-stations

A.1. Validation of HelioClim-3 version 4 (HC3v4) and 5 (HC3v5) versus the measurements of 14 BSRN stations for the daily and 15 min GHI

Table 3. Daily sum of 15 min HC3v4 and v5 GHI values. Units are kWh m^{-2}.

Station	Number of values	Mean BSRN	Bias HC3v4 (relative in %)	Bias HC3v5 (relative in %)	RMSE HC3v4 (relative in %)	RMSE HC3v5 (relative in %)	Correl. coeff. HC3v4	Correl. coeff. HC3v5
Lerwick	885	2668.1	85.9 (3.2%)	125.1 (4.7%)	470.3 (17.6%)	443.4 (16.6%)	0.972	0.977
Toravere	2977	2830.0	-68.0 (-2.4%)	-102.4 (-3.6%)	439.3 (15.5%)	404.7 (14.3%)	0.979	0.983
Lindenberg	1110	2998.9	-140.3 (-4.7%)	-129.5 (-4.3%)	392.1 (13.1%)	385.7 (12.9%)	0.987	0.987
Cabauw	3313	2958.2	-116.8 (-3.9%)	-79.6 (-2.7%)	385.9 (13.0%)	346.1 (11.7%)	0.986	0.988
Camborne	1202	3181.3	-35.6 (-1.1%)	7.0 (0.2%)	319.0 (10.0%)	293.0 (9.2%)	0.990	0.992
Palaiseau	2814	3244.4	117.0 (3.6%)	72.9 (2.2%)	332.2 (10.2%)	279.7 (8.6%)	0.991	0.993
Payerne	2543	3345.3	-270.6 (-8.1%)	-41.6 (-1.2%)	477.4 (14.3%)	385.1 (11.5%)	0.986	0.987
Carpentras	3536	4378.6	55.0 (1.3%)	72.2 (1.7%)	335.6 (7.7%)	286.1 (6.5%)	0.991	0.994
Cener	1251	3987.1	103.9 (2.6%)	128.7 (3.2%)	356.1 (8.9%)	349.0 (8.8%)	0.990	0.991
Sede Boqer	2893	5763.4	-380.8 (-6.6%)	-253.1 (-4.4%)	534.7 (9.3%)	409.7 (7.1%)	0.982	0.987
Tamanrasset	3483	6001.3	41.5 (0.7%)	78.4 (1.3%)	563.1 (9.4%)	437.8 (7.3%)	0.925	0.957
Brasilia	1882	5246.9	241.3 (4.6%)	158.0 (3.0%)	638.0 (12.2%)	575.7 (11.0%)	0.900	0.915
Sao Martinho da Serra	2169	4780.0	-13.1 (-0.3%)	-99.6 (-2.1%)	414.9 (8.7%)	383.9 (8.0%)	0.985	0.989
De Aar	330	5724.0	2.6 (0.0%)	-13.1 (-0.2%)	410.3 (7.2%)	320.9 (5.6%)	0.981	0.988

Table 4. 15 min HC3v4 and v5 GHI values. Units are kWh m^{-2}.

Station	Number of values	Mean BSRN	Bias HC3v4 (relative in %)	Bias HC3v5 (relative in %)	RMSE HC3v4 (relative in %)	RMSE HC3v5 (relative in %)	Correl. coeff. HC3v4	Correl. coeff. HC3v5
Lerwick	44690	53.0	1.7 (3.3%)	2.5 (4.7%)	20.0 (37.7%)	19.7 (37.2%)	0.915	0.920
Toravere	141091	61.9	-1.6 (-2.6%)	-2.4 (-3.8%)	21.1 (34.0%)	20.5 (33.0%)	0.930	0.935
Lindenberg	50550	65.9	-3.1 (-4.7%)	-2.8 (-4.3%)	19.8 (30.0%)	19.5 (29.6%)	0.941	0.942
Cabauw	151766	64.9	-2.5 (-3.9%)	-1.7 (-2.7%)	19.5 (30.0%)	19.0 (29.4%)	0.941	0.944
Camborne	55822	68.7	-0.8 (-1.1%)	0.2 (0.2%)	18.1 (26.3%)	17.8 (25.9%)	0.954	0.956
Palaiseau	129095	70.9	2.6 (3.6%)	1.6 (2.2%)	18.1 (25.5%)	17.6 (24.8%)	0.955	0.957
Payerne	114535	76.1	-6.2 (-8.2%)	-1.0 (-1.3%)	21.7 (28.5%)	20.5 (27.0%)	0.949	0.951
Carpentras	164112	94.4	1.2 (1.3%)	1.6 (1.7%)	15.8 (16.7%)	15.4 (16.3%)	0.974	0.976
Cener	57979	87.8	2.3 (2.6%)	2.9 (3.3%)	19.2 (21.8%)	19.2 (21.9%)	0.961	0.961
Sede Boqer	128614	133.1	-8.7 (-6.5%)	-5.7 (-4.3%)	20.4 (15.3%)	18.8 (14.1%)	0.970	0.973
Tamanrasset	162631	133.0	0.9 (0.7%)	1.6 (1.2%)	22.4 (16.9%)	21.0 (15.8%)	0.962	0.967
Brasilia	87250	115.1	5.4 (4.7%)	3.6 (3.1%)	38.1 (33.1%)	37.3 (32.4%)	0.882	0.885
Sao Martinho da Serra	99192	105.2	-0.2 (-0.2%)	-2.2 (-2.1%)	24.9 (23.7%)	24.3 (23.1%)	0.949	0.952
De Aar	14636	129.3	0.0 (0.0%)	-0.3 (-0.2%)	19.7 (15.2%)	18.7 (14.4%)	0.967	0.971

A.2. Validation of HelioClim-3 version 4 (HC3v4) and 5 (HC3v5) versus the measurements of 14 BSRN stations for the daily and 15 min direct normal irradiation

Table 5. Daily sum of 15 min HC3v4 and v5 DNI values. Units are kWh m^{-2}.

Station	Number of values	Mean BSRN	Bias HC3v4 (relative in %)	Bias HC3v5 (relative in %)	RMSE HC3v4 (relative in %)	RMSE HC3v5 (relative in %)	Correl. coeff. HC3v4	Correl. coeff. HC3v5
Lerwick	252	4234.4	389.0 (9.2%)	798.8 (18.9%)	1505.5 (35.6%)	1641.8 (38.8%)	0.843	0.853
Toravere	1154	6389.0	-873.5 (-13.7%)	-913.9(-14.3%)	1840.3 (28.8%)	1576.5 (24.7%)	0.844	0.896
Lindenberg	513	5218.4	-229.2 (-4.4%)	-217.1 (-4.2%)	1300.3 (24.9%)	1218.9 (23.4%)	0.873	0.887
Cabauw	1525	4624.6	42.0 (0.9%)	247.7 (5.4%)	1163.8 (25.2%)	1043.2 (22.6%)	0.889	0.918
Camborne	491	4923.9	219.8 (4.5%)	509.8 (10.4%)	1194.2 (24.3%)	1141.4 (23.2%)	0.905	0.928
Palaiseau	1640	5001.4	440.4 (8.8%)	299.0 (6.0%)	1345.5 (26.9%)	1075.4 (21.5%)	0.876	0.914
Payerne	1095	6122.4	-773.7 (-12.6%)	272.6 (4.5%)	1467.8 (24.0%)	1185.0 (19.4%)	0.876	0.898
Carpentras	2691	6598.6	-217.8 (-3.3%)	-94.3 (-1.4%)	1331.4 (20.2%)	1081.3 (16.4%)	0.860	0.914
Cener	807	5994.8	21.9 (0.4%)	130.3 (2.2%)	1276.0 (21.3%)	1138.0 (19.0%)	0.886	0.918
Sede Boqer	2646	6668.3	-1105.4 (-16.6%)	-811.1(-12.2%)	1703.2 (25.5%)	1346.4 (20.2%)	0.811	0.883
Tamanrasset	2960	6767.0	575.5 (8.5%)	793.0 (11.7%)	2111.1 (31.2%)	1759.1 (26.0%)	0.558	0.790
Brasilia	1312	5674.9	383.3 (6.8%)	258.8 (4.6%)	1365.6 (24.1%)	1155.4 (20.4%)	0.823	0.872
Sao Martinho da Serra	975	6573.5	-139.3 (-2.1%)	-269.7 (-4.1%)	1372.3 (20.9%)	1120.7 (17.0%)	0.857	0.924
De Aar	327	8415.9	-848.2 (-10.1%)	-842.3(-10.0%)	1507.1 (17.9%)	1257.3 (14.9%)	0.908	0.943

Table 6. 15 min HC3v4 and v5 DNI values. Units are kWh m-2.

Station	Number of values	Mean BSRN	Bias HC3v4 (relative in %)	Bias HC3v5 (relative in %)	RMSE HC3v4 (relative in %)	RMSE HC3v5 (relative in %)	Correl. coeff. HC3v4	Correl. coeff. HC3v5
Lerwick	19410	77.1	15.5 (20.1%)	21.9 (28.4%)	59.6 (77.4%)	62.5 (81.0%)	0.647	0.663
Toravere	83701	116.0	-12.8 (-11.1%)	-15.0 (-12.9%)	58.1 (50.0%)	54.8 (47.2%)	0.724	0.766
Lindenberg	30697	99.5	-2.6 (-2.6%)	-1.9 (-1.9%)	48.0 (48.3%)	48.0 (48.3%)	0.765	0.775
Cabauw	90895	90.5	3.1 (3.4%)	6.8 (7.5%)	45.9 (50.7%)	46.4 (51.3%)	0.772	0.789
Camborne	29704	94.1	8.7 (9.3%)	13.8 (14.6%)	47.6 (50.6%)	48.3 (51.4%)	0.782	0.800
Palaiseau	94608	98.3	12.6 (12.8%)	9.6 (9.7%)	48.6 (49.5%)	46.3 (47.1%)	0.778	0.799
Payerne	67261	120.8	-14.7 (-12.2%)	6.3 (5.2%)	50.5 (41.8%)	49.7 (41.1%)	0.793	0.808
Carpentras	132403	139.8	-2.3 (-1.6%)	0.2 (0.1%)	45.7 (32.7%)	44.4 (31.8%)	0.791	0.814
Cener	43038	123.2	4.2 (3.4%)	6.5 (5.3%)	48.6 (39.4%)	48.9 (39.7%)	0.795	0.801
Sede Boqer	118265	155.4	-25.0 (-16.1%)	-17.9 (-11.5%)	55.0 (35.4%)	50.6 (32.6%)	0.761	0.795
Tamanrasset	143914	151.2	18.9 (12.5%)	21.7 (14.4%)	63.4 (41.9%)	57.6 (38.1%)	0.681	0.768
Brasilia	65389	125.0	12.2 (9.8%)	8.3 (6.7%)	63.4 (50.7%)	60.3 (48.2%)	0.674	0.705
Sao Martinho da Serra	48481	141.5	-0.5 (-0.3%)	-4.3 (-3.1%)	58.0 (41.0%)	55.4 (39.1%)	0.736	0.766
De Aar	15099	187.2	-16.8 (-9.0%)	-17.4 (-9.3%)	50.9 (27.2%)	48.2 (25.8%)	0.767	0.808

A.3. Validation of MACC-RAD versus the measurements of 14 BSRN stations for the daily and 15 min global horizontal irradiation

Table 7. Daily sum of 15 min MACC-RAD GHI values. Units are kWh m-2.

Station	Number of values	Mean BSRN	Bias MACC-RAD (relative in %)	RMSE MACC-RAD (relative in %)	Correl. coeff. MACC-RAD
Lerwick	1068	2264.6	126.9 (5.6%)	453.9 (20.0%)	0.975
Toravere	3542	2425.5	95.3 (3.9%)	445.2 (18.4%)	0.980
Lindenberg	1121	3005.0	161.6 (5.4%)	507.6 (16.9%)	0.979
Cabauw	3321	2960.6	357.5 (12.1%)	591.1 (20.0%)	0.980
Camborne	1213	3183.9	330.2 (10.4%)	558.3 (17.5%)	0.982
Palaiseau	2816	3244.0	293.1 (9.0%)	520.6 (16.0%)	0.983
Payerne	2553	3344.2	332.4 (9.9%)	542.7 (16.2%)	0.984
Carpentras	3547	4378.5	244.8 (5.6%)	428.1 (9.8%)	0.990
Cener	1251	3987.1	190.5 (4.8%)	486.8 (12.2%)	0.982
Sede Boqer	2899	5763.0	13.4 (0.2%)	414.4 (7.2%)	0.981
Tamanrasset	3494	6000.1	128.5 (2.1%)	451.0 (7.5%)	0.961
Brasilia	1883	5247.5	373.0 (7.1%)	719.5 (13.7%)	0.900
Sao Martinho da Serra	2170	4780.2	149.4 (3.1%)	496.1 (10.4%)	0.980
De Aar	332	5717.8	40.1 (0.7%)	465.9 (8.1%)	0.976

Table 8. 15 min MACC-RAD GHI values. Units are kWh m-2.

Station	Number of values	Mean BSRN	Bias MACC-RAD (relative in %)	RMSE MACC-RAD (relative in %)	Correl. coeff. MACC-RAD
Lerwick	49001	49.6	2.8 (5.7%)	21.0 (42.3%)	0.905
Toravere	154250	57.8	2.2 (3.8%)	22.2 (38.4%)	0.922
Lindenberg	51076	66.0	3.6 (5.4%)	22.4 (33.9%)	0.928
Cabauw	152161	64.9	7.8 (12.1%)	23.4 (36.1%)	0.929
Camborne	56335	68.7	7.1 (10.4%)	22.8 (33.2%)	0.938
Palaiseau	129175	70.9	6.4 (9.0%)	22.3 (31.4%)	0.939
Payerne	114969	76.1	7.6 (10.0%)	23.0 (30.2%)	0.947
Carpentras	164642	94.4	5.3 (5.6%)	18.5 (19.6%)	0.968
Cener	57979	87.8	4.2 (4.8%)	22.6 (25.8%)	0.947
Sede Boqer	128894	133.1	0.3 (0.2%)	19.6 (14.7%)	0.968
Tamanrasset	163126	133.0	2.8 (2.1%)	23.0 (17.3%)	0.961
Brasilia	87297	115.1	8.4 (7.3%)	39.2 (34.0%)	0.879
Sao Martinho da Serra	99238	105.2	3.3 (3.1%)	27.1 (25.8%)	0.941
De Aar	14734	129.1	0.9 (0.7%)	23.5 (18.2%)	0.955

A.4. Validation of MACC-RAD versus the measurements of 14 BSRN stations for the daily and 15 min direct normal irradiation

Table 9. Daily sum of 15 min MACC-RAD DNI values. Units are kWh m^{-2}.

Station	Number of values	Mean BSRN	Bias MACC-RAD (relative in %)	RMSE MACC-RAD (relative in %)	Correl. coeff. MACC-RAD
Lerwick	291	3792.3	-1389.8 (-36.6%)	1859.4 (49.0%)	0.882
Toravere	1247	6056.0	-1964.6 (-32.4%)	2354.4 (38.9%)	0.920
Lindenberg	521	5226.9	-844.6 (-16.2%)	1223.9 (23.4%)	0.952
Cabauw	1529	4627.5	-412.4 (-8.9%)	1044.4 (22.6%)	0.935
Camborne	498	4923.5	-240.3 (-4.9%)	1061.8 (21.6%)	0.938
Palaiseau	1647	5006.0	-475.1 (-9.5%)	1086.7 (21.7%)	0.939
Payerne	1099	6123.1	-327.8 (-5.4%)	1163.7 (19.0%)	0.926
Carpentras	2698	6600.3	-289.2 (-4.4%)	905.3 (13.7%)	0.952
Cener	807	5994.8	-566.2 (-9.4%)	1084.6 (18.1%)	0.952
Sede Boqer	2651	6665.5	-1015.1 (-15.2%)	1640.4 (24.6%)	0.879
Tamanrasset	2969	6761.3	447.3 (6.6%)	1393.5 (20.6%)	0.848
Brasilia	1313	5675.2	99.6 (1.8%)	1370.0 (24.1%)	0.878
Sao Martinho da Serra	976	6571.6	-459.5 (-7.0%)	1443.9 (22.0%)	0.884
De Aar	328	8411.9	-393.7 (-4.7%)	1013.8 (12.1%)	0.940

Table 10. 15 min MACC-RAD DNI values. Units are kWh m^{-2}.

Station	Number of values	Mean BSRN	Bias MACC-RAD (relative in %)	RMSE MACC-RAD (relative in %)	Correl. coeff. MACC-RAD
Lerwick	21069	74.0	-29.7 (-40.2%)	62.7 (84.7%)	0.665
Toravere	86898	114.4	-41.8 (-36.5%)	73.6 (64.3%)	0.707
Lindenberg	31105	99.8	-18.5 (-18.5%)	51.2 (51.3%)	0.799
Cabauw	91164	90.6	-8.9 (-9.8%)	48.3 (53.3%)	0.779
Camborne	30073	94.2	-5.7 (-6.0%)	49.5 (52.5%)	0.797
Palaiseau	94992	98.4	-11.2 (-11.4%)	48.2 (49.0%)	0.809
Payerne	67562	120.7	-8.7 (-7.2%)	51.0 (42.3%)	0.812
Carpentras	132820	139.8	-7.1 (-5.1%)	40.1 (28.7%)	0.873
Cener	43038	123.2	-14.0 (-11.3%)	49.1 (39.8%)	0.841
Sede Boqer	118483	155.3	-25.0 (-16.1%)	59.2 (38.1%)	0.768
Tamanrasset	144308	151.1	11.5 (7.6%)	51.1 (33.8%)	0.821
Brasilia	65435	125.0	-0.1 (-0.1%)	66.3 (53.0%)	0.725
Sao Martinho da Serra	48527	141.4	-11.3 (-8.0%)	65.9 (46.6%)	0.747
De Aar	15176	186.7	-9.0 (-4.8%)	48.6 (26.0%)	0.833

References

[1] Rigollier C, Lefevre M, and Wald L. The method Heliosat-2 for deriving shortwave solar radiation from satellite images. Solar Energy 2004;77:159–169

[2] Gschwind B., Ménard L., Albuisson M., Wald L., Converting a successful research project into a sustainable service: the case of the SoDa Web service. Environmental Modelling and Software 2006, 21, 1555-1561

[3] Hoyer-Klick C, Lefèvre M, Schroedter-Homscheidt M, Wald L. User's guide to the MACC-RAD Services on solar energy radiation resources, March 2015. https://www.gmes-atmosphere.eu/documents/macciii/deliverables/rad/MACCIII_RAD_DEL_D57.5_final.pdf

[4] Blanc Ph., Gschwind B., Lefèvre M., Wald L., The HelioClim project: Surface solar irradiance data for climate applications. Remote Sensing, 2011, 3, 343-361

[5] Rigollier C, Bauer O, Wald L. On the clear sky model of the 4th European Solar Radiation Atlas with respect to the Heliosat method. Solar Energy 2000;68:33-48

[6] Remund J., Wald L., Lefèvre M., Ranchin T., Page J. Worldwide Linke turbidity information. Proceedings of ISES Solar World Congress, 16-19 June 2003, Göteborg, Sweden.

[7] Lefevre M, Oumbe A, Blanc P, Espinar B, Gschwind B, Qu Z, Wald L, Schroedter-Homscheidt M, Hoyer-Klick C, Arola A, Benedetti A, Kaiser J W, Morcrette J J. McClear: a new model estimating downwelling solar radiation at ground level in clear-sky conditions. Atmos. Measur. Tech. 2013;6:2403–2418

[8] Qu Z, Gschwind B, Lefevre M, Wald L. Improving HelioClim-3 estimates of surface solar irradiance using the McClear clear-sky model and recent advances in atmosphere composition. Atmos. Meas. Tech. 2014;7:3927–3933

[9] Oumbe A., Qu Z., Blanc P., Lefevre M., Wald L., Cros S. Technical Note - Decoupling the effects of clear atmosphere and clouds to simplify calculations of the broadband solar irradiance at ground level. Geosci. Model Dev. 2014, 7, 1661-1669

[10] König-Langlo, Gert; Bücker, Amelie; Richter, Friedrich; Sieger, Rainer (2014): BSRN snapshot 2014-06 in two ZIP archives (5.63 GB). doi:10.1594/PANGAEA.833428

[11] Ohmura, A., Gilgen, H., Hegner, H., Mueller, G., Wild, M., Dutton, E. G., Forgan, B., Froelich, C., Philipona, R., Heimo, A., Koenig-Langlo, G., McArthur, B., Pinker, R., Whitlock, C. H., and Dehne, K.: Baseline Surface Radiation Network (BSRN/WCRP): New precision radiometry for climate research. B. Am. Meteorol. Soc. 1998, 79, 2115–2136

[12] Roesch, A., Wild, M., Ohmura, A., Dutton, E.G., Long, C.N., and Zhang, T.: Assessment of BSRN radiation records for the computation of monthly means, Atmos. Meas. Tech., 4, 339–354, doi:10.5194/amt-4-339-2011, 2011. Corrigendum, Atmos. Meas. Tech., 4, 973-973, doi:10.5194/amt-4-973-2011, 2011.

[13] WMO. Technical Note N° 172, WMO-No. 554, World Meteorological Organization, Geneva, Switzerland, 1981, p. 121-123